frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 24 January 2025
DOI 10.3389/fenvs.2024.1535193

OPEN ACCESS

EDITED BY
Xiaoping Wang,
Northwest A&F University, China

REVIEWED BY
Chenfeng Wang,
Chinese Academy of Sciences (CAS), China
Meng Wang,
Chaozhou Environmental Information Center,
China

*CORRESPONDENCE
Zhongju Meng,
✉ mengzhongju@126.com

RECEIVED 27 November 2024
ACCEPTED 27 December 2024
PUBLISHED 24 January 2025

CITATION
Yang Y, Meng Z, Li H, Gao Y, Li T and Qin L (2025) Soil porosity as a key factor of soil aggregate stability: insights from restricted grazing.
Front. Environ. Sci. 12:1535193.
doi: 10.3389/fenvs.2024.1535193

Soil porosity as a key factor of soil aggregate stability: insights from restricted grazing

Yi Yang[1,2,3], Zhongju Meng[1,2,3]*, Haonian Li[1,2,3], Yue Gao[1,2,3], Tianyang Li[1,2,3] and Lei Qin[4]

[1]College of Desert Control Science and Engineering, Inner Mongolia Agricultural University, Hohhot, China, [2]Key Laboratory of Aeolian Physics and Desertification Control Engineering from Inner Mongolia Autonomous Region, Inner Mongolia Agricultural University, Hohhot, China, [3]Key Laboratory of Desert Ecosystem Conservation and Restoration, State Forestry and Grassland Administration of China, Inner Mongolia Agricultural University, Hohhot, China, [4]Inner Mongolia Water Conservancy Development Center, Hohhot, China

Overgrazing leads to steppe degradation and soil structure deterioration, which is common in desert steppes. Restricted grazing is a sustainable practice, but the mechanisms by which soil structure responds to restricted grazing have received little attention. This study examined the effects of two different grazing management strategies, namely, restricted grazing and free grazing (CK), on soil structure indicators in the desert steppe. The restricted grazing further included grazing exclusion (GE) and seasonal grazing (SG). Additionally, a preliminary exploration was conducted to identify the main factors affecting the soil aggregate stability. Our results demonstrated that GE significantly increased clay (<0.002 mm) and silt (0.002–0.02 mm) in the 0–10 cm and 10–20 cm layers by an average of 71.27% and 70.64%, respectively. Additionally, SG significantly increased clay (<0.002 mm), silt (0.002–0.02 mm), and macroaggregates (>0.25 mm) in the 0–10 cm layer. GE significantly increased soil organic carbon in the 0–10 cm and 10–20 cm layers by 7.02 g/kg and 7.45 g/kg, respectively. In addition, SG had no significant effect on soil organic carbon. The findings obtained from the computations using the boosted regression tree (BRT) demonstrated that, within the study period, soil porosity significantly affects soil aggregate stability compared to other factors. Moreover, it possessed an average explanatory power that surpassed 45%. Overall, the soil structure is better under GE than under SG, and GE is the key to improving the soil structure of desert steppe. The research will contribute to a more profound comprehension of the impact of grazing on soil structure. Therefore, it is recommended that grazing closures be prioritized in desert grasslands to promote coordination between grassland restoration and livestock development.

KEYWORDS

soil aggregate stability, desert steppe, soil organic carbon, grazing exclusion, soil porosity

1 Introduction

Steppe ecosystems are a vital component of the natural environment, covering approximately 40% of the total land area and serving numerous ecological and productive roles (Tian et al., 2021; Liu et al., 2023). These ecosystems predominantly exist in arid and semiarid regions susceptible to global environmental changes, characterized by fragile ecosystems and a high risk of soil erosion. Soil dispersion and water permeability properties significantly contribute to soil erosion vulnerability. Good soil structure is critical for enhancing soil stability and effectively combating erosion (Abu-Hamdeh et al., 2006; Kinnell, 2018; Gao et al., 2024). The dual nature of soil structure can be delineated as the unity of aggregates and pores. In the long run, soil aggregates have a more comprehensive range of functions than pore space alone (Yudina and Kuzyakov, 2023). Soil aggregate formation increases soil cohesion and reduces soil erosion (Yudina and Kuzyakov, 2019; Phefadu and Munjonji, 2024). Also, soil aggregates have comparable water-holding and aerated pore space, and the soil is highly permeable, which also favors erosion resistance (Ferreira et al., 2023). As early as 1983, it was pointed out that soil aggregate stability indicates the indices of soil erodibility (Egashlra et al., 1983). In the Water Erosion Prediction Project (WEPP) model, Agglomerate stability is also recognized as one of the most critical soil indicators for soil erosion (Karlen and Stott, 2015; Xiao et al., 2017; Zhu et al., 2018).

The utilization of steppe ecosystems for grazing represents a pivotal aspect of their management, exerting a considerable influence on the configuration and functionality of these ecosystems (Reinhart et al., 2021). Soil erosion and degradation of grassland ecosystem services and functions caused by inappropriate grazing have become a global problem (Zhang et al., 2018; Bardgett et al., 2021). It is estimated that the degraded grassland area in China has reached 90% (Zhu et al., 2021). It is imperative to identify suitable grazing practices that can alleviate grassland degradation and ensure the long-term stability of grassland ecosystems (Rojas-Briales, 2015).

Since the 1960s, grassland privatization has led to the loss of self-recovery of desert steppe in northern China and reduced soil productivity (Conte and Tilt, 2014; Ye et al., 2023). This severe consequence has prompted the government to prioritize this issue. In 2003, a ‘Returning Grazing Land to Grassland’ policy was introduced to restore degraded steppe, including grazing bans and seasonal grazing (Li et al., 2013). The objective of these measures is twofold: firstly, to enhance plant diversity and, secondly, to restore the functioning of steppe ecosystems by improving soil structure through a series of reciprocal mechanisms (Franzluebbers et al., 2012; Enriquez et al., 2021; Nael et al., 2024; Blanco-Sepúlveda et al., 2024). Different grazing patterns affect the degree of soil disturbance, which in turn causes dynamic changes in soil structure indicators (Blanco and Lal, 2023). Therefore, research on grassland restoration should focus on the response of soil structure indicators to changes in grazing patterns (De Boer et al., 2018; Lai and Kumar, 2020). Conversely, the evidence suggests that moderate grazing can help offset these impacts, although this approach does result in a corresponding decrease in soil organic carbon (Lai and Kumar, 2020). A reduction in grazing levels results in a notable decrease in soil compaction, primarily caused by livestock trampling (Romero-Ruiz et al., 2023). A systematic framework has been developed to predict changes in soil structural properties associated with livestock-induced soil compaction (Romero-Ruiz et al., 2023). Seasonal grazing promotes sustained restoration of grassland soils by reducing the duration of grazing, but scientists have paid little attention to it (Chen and Baoyin, 2024). One of the few examples is a study in a typical steppe in China, which demonstrated that seasonal grazing can reduce the adverse effects of grazing on pore characteristics (Yang et al., 2024).

Many studies have been conducted on the effects of grazing on grassland soil aggregates. These studies have shown that grazing exclusion significantly increases the number and stability of soil aggregates, as well as the erosion resistance of soils. These studies have attributed the improved stability of soil aggregates to increased organic carbon (Deng et al., 2018; Dong et al., 2022). Other studies point out that soil texture controls the formation of specific aggregates, where larger-diameter aggregates are positively correlated with increased clay content (Schweizer et al., 2019). Some other studies have shown a significant positive correlation between porosity and soil aggregate stability. During the decomposition of plant residues by microorganisms, phenolic acids are released. At the same time, the decomposition of amino acids in the residues triggers an instantaneous stabilization of the aggregates. The interaction of phenolic acids with the instantly formed aggregates further enhances the soil aggregates stability (Martens, 2000). The contradictory results of these studies prompted us to explore the main factors affecting the soil aggregate stability.

This study utilizes a 20-year-long field experiment to fill this gap in the mechanisms by which soil structure indicators respond to restricted grazing and to explore differences in scores of factors influencing soil aggregate stability in a desert steppe. Three field observation sites were established using fences to desert steppe in Inner Mongolia, these were designated as grazing exclusion (GE), seasonal grazing (SG), and free grazing (CK), each defined by fenced boundaries. Therefore, the research objectives of this study were defined as follows: (1) To assess the effects of different grazing practices on soil structure indicators, quantitatively evaluate soil particle size composition, soil bulk density, soil aggregate composition, soil aggregate stability, and soil organic carbon under varying grazing practices; and (2) To explore the primary factors influencing changes in soil aggregate stability. The results of this experiment aim to provide a theoretical foundation for the adaptive management of steppe ecosystems and contribute to efforts to slow down or reverse steppe degradation.

2 Materials and methods

2.1 Overview of the Study area

The study area is in Baotou, Inner Mongolia, within the southeastern portion of Darhan Muminggan United Banner (coordinates: 41° 21′3.96″N, 111° 12′35.79″E) (Figure 1). It is at approximately 1600 m and has a semiarid continental climate. The annual mean temperature is 3.4°C, the annual mean rainfall is 282 mm, and the annual mean evapotranspiration is 2,225 mm. The soil in this area is calcareous, with a thin humus layer and low organic matter content, and the soil layer is about 40 cm deep. The dominant plant taxa are *Stipa grandis, Leymus chinensis*, *Agropyron cristarum*, and *Cleistogenes squarrosa*.

2.2 Experimental design and soil sampling

The experiment was conducted at the Yinshanbeilu Grassland Eco-hydrology National Observation and Research Station

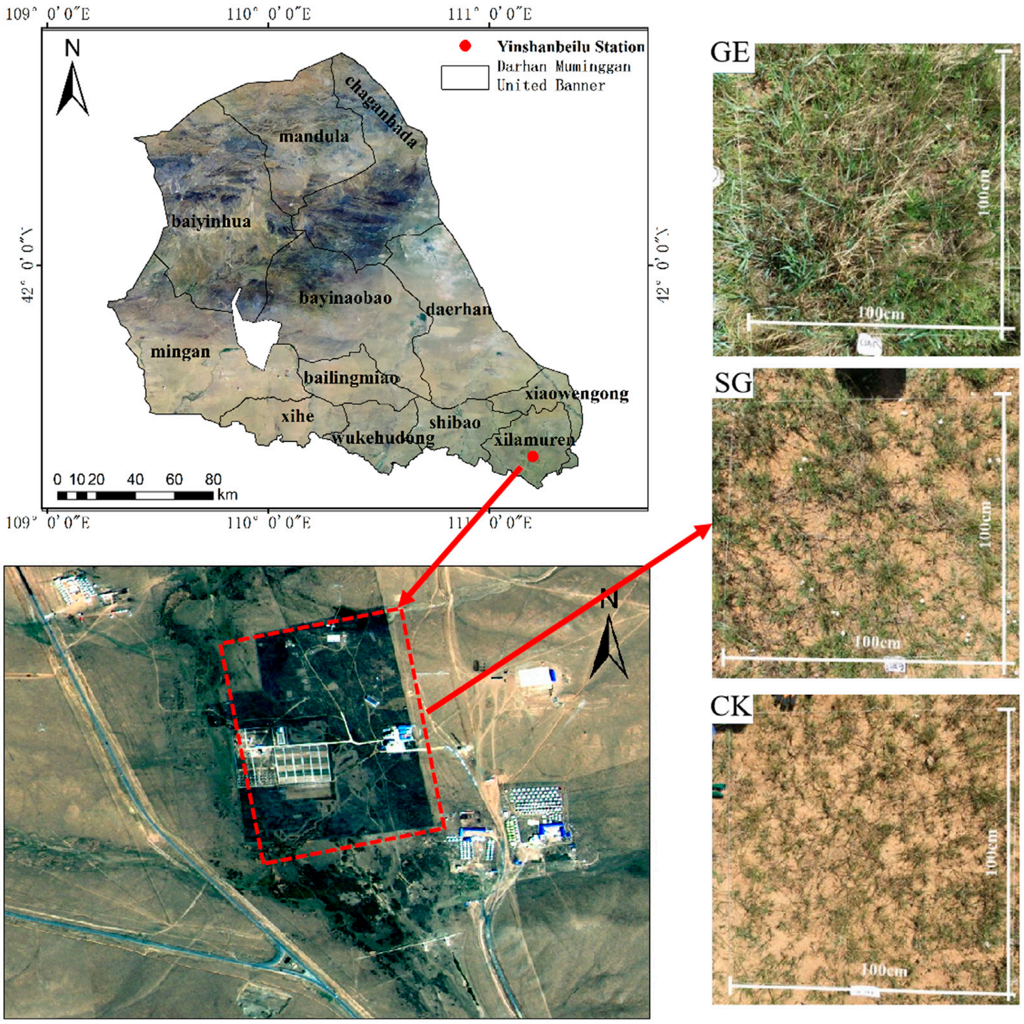


FIGURE 1
Study area. NOTE:GE: grazing exclusion; SG: seasonal grazing; CK: free grazing.

(Yinshanbeilu Station). Three grazing plots were established: restricted grazing (GE and SG) plots were set up on flat terrain under similar natural conditions, and CK in the periphery was set as a control. According to the Yinshanbeilu Station records, the area has been grazed since 1960. The three plots were adjacent and at the same altitude to prevent climate and other factors from influencing the experimental results.

To ensure the greatest possible consistency in grazing intensity, the specifications of plots were varied. Among them: (1) The GE plot has been closed to grazing since 2002, using a 2.0 m wire mesh fence to exclude livestock. The sample plot size was 400 m × 300 m, with no grazing activities, and the vegetation coverage is approximately 92.10%. (2) The SG plot, seasonal grazing (November to April), was introduced in 2002 and enclosed with a 2.0 m barbed wire fence. The sample plot size was 300 m × 250 m, with a grazing intensity of 0.5-1 sheep ha^{-1}, and the vegetation coverage is approximately 60.10%. (3) The CK plot has been fenced off with barbed wire since 2002 and has been under continuous grazing by local herders. The size of the sample plot was 400 m × 200 m. The grazing intensity ranges from 0.5 - 1 sheep ha^{-1} between November and April and 1–1.5 sheep ha^{-1} from May to October, and the vegetation coverage is approximately 48.80%. Each plot adopts the same grazing system as the local herders, feeding from 7:00 to 19:00 and driving back to the sheepfolds to rest in the evening. Three 20 m × 20 m test plots were randomly established as replicates within each grazing method sample plot.

Three 1 m × 1 m sample plots were randomly picked from each grazing area, swith a slope of 2.2°–3.0°. Subsequently, the soil samples were collected in layers from different depths, including 0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm, by utilizing a 100 cm^3 sampling ring. It is worth noting that no rainfall occurred during the initial 10 days at the sampling locations, nullifying any potential influence that rain could have exerted on the soil characteristics.

2.3 Analysis of soil samples

The mechanical composition of the soil was determined as follows: First, the air-dried soil was crushed, and any foreign matter was removed. Then, the resulting material was passed through a 2 mm sieve. After that, a Malvern Mastersizer-3000 (Malvern Instruments Ltd., Malvern, UK) model laser particle sizer was used to determine the soil particle size composition for further analysis. Finally, the results were classified by the International Standard Classification of Soils (ISCS). SOC was measured with $K_2Cr_2O_7$-H_2SO_4 (Noulèkoun et al., 2021). The samples collected by the ring knife ($V = 100\ cm^3$) were divided into two groups. A group of soil samples was placed in an oven at a temperature of 105°C ± 2°C, dried to a constant weight, and then weighed (G_s, g). The other set of soil samples was divided into two, weighed and soaked in static water for 1–2 h and 6 h and taken out for weighing respectively. Based on the above measurement, soil bulk density (BD), total porosity (TP), capillary porosity (CP), and non-capillary porosity (NCP) were calculated by Equations 1–4.

$$BD = G_s/V \tag{1}$$

$$TP = (W_{6H} - W_1 - W_D)/V \tag{2}$$

$$CP = (W_{2H} - W_1 - W_D)/V \tag{3}$$

$$NCP = TP - CP \tag{4}$$

Where: W_1:weight of ring cutter(g);W_{6H} is weight of ring cutter with soil after 6 h of water absorption (g);W_{2H} is weight of ring cutter with soil after 2 h of water absorption (g).

The soil clumps within the soil samples were manually fragmented into pieces with a diameter of approximately 10 mm. After air-drying, extraneous substances were meticulously removed with the assistance of tweezers. Subsequently, a 50 g sample was procured and placed into the sieve set of the DIK-2012 Aggregate Analyzer. The sieve set is configured with apertures of 2 mm, 1 mm, 0.5 mm, and 0.25 mm. Distilled water was gradually added along the bucket's rim until it covered the soil samples completely. Following a stationary period of 2 min, the shaking process was initiated at 30 oscillations per minute with a shaking amplitude of 38 mm. The shaking operation was concluded after 5 min. The remaining soil particles in the various sieves were then dried to a constant weight on an electric hot plate maintained at 60°C. They were subsequently weighed, and the proportions of water-stable aggregates of different particle sizes were accurately calculated. The soil aggregates were weighed and used to calculate soil aggregate fractions. To assess the aggregate stability, three metrics, $WSA_{>0.25}$(water-stable aggregate >0.25 mm), MWD (mean weight diameter), and GMD (geometric mean diameter), were calculated. Calculations were made by means of Equations 5–7.

$$WSA_{>0.25} = \frac{M_s}{M_t} \tag{5}$$

Where: M_s is the amount of >0.25 mm water stable aggregates (g), and M_t is the total amount of aggregate before wet sieving (g).

$$MWD = \sum_{i=1}^{n} \left(\overline{x_i} W_i\right) \Big/ \sum_{i}^{n} W_i \tag{6}$$

Where: x_i is the average diameter of aggregate of particle size i and ω_i is the percentage content of aggregate of particle size i.

$$GMD = \exp\left(\sum_{i=1}^{n} \omega_i \ln \overline{x_i} \Big/ \sum_{i}^{n} \omega_i\right) \tag{7}$$

Where: x_i is the average diameter (mm) of aggregate of particle size i, and ω_i is the percentage content (%) of particle size i.

2.4 Statistics and analysis of data

Before conducting an Analysis of Variance (ANOVA), the data's normal distribution and homogeneity of variance were tested. Least Significance Difference (LSD) and Duncan tests are employed for multiple comparisons to analyze the differences among different grazing practices. The significance of all differences is tested using SPSS version 25.0 at a significance level of $p < 0.05$.

The relative effects of the factors on overall stability were quantitatively assessed using a Boosted Regression Tree (BRT) model by selecting parameter combinations that ensured an R^2 greater than 0.8 and a Mean Squared Error (MSE) less than 0.1. The specific parameters are "distribution = gaussian,trees = 5000,interaction.depth = 1,shrinkage = 0.06, bag.fraction = 0.8" (Sidhu et al., 2023). The BRT model was implemented using the Dismo package in R version 4.2.3.

3 Results

3.1 Soil particle size composition and soil texture characteristics

The soil particle size composition for different grazing regimes is shown below (Table 1). The composition of the soil particle size of the soil (excluding 20–30 cm) differed significantly ($p < 0.05$) among the three grazing methods. The percentages of the total volume of different grain sizes in the sample graphs for the grazing methods showed the same pattern: sand > silt > clay. Under GE and SG, the volume distribution of soil grain sizes decreased in the sand and increased in silt and clay compared with the CK ($p < 0.05$). At 0–10 cm, the sand in GE and SG was significantly lower than in CK ($p < 0.05$). The reduction in sand in SG (72.85% ± 2.36%) was more significant than that in GE (75.66% ± 4.64%). Similarly, the clay and silt were significantly increased, and the increase in SG was higher than that in GE ($p < 0.05$). Nevertheless, at depths of 10–20 cm and 30–40 cm, the impact of the reduction in sand and the increase in silt and clay was more pronounced in GE than in SG. Conversely, at a depth of 20–30 cm, no statistically significant difference was observed in the sand, silt, and clay among GE, SG, and CK ($p > 0.05$). Nevertheless, it is worth noting that the soil texture within the GE and SG plots has improved when juxtaposed with that of the CK plot (Figure 2).

3.2 Soil bulk density and porosity characteristics

Table 2 summarizes the BD, TP, CP, and NCP for the three different grazing management practices at various soil depths. At 0–10 cm, BD and TP showed no statistically significant differences among GE, SG, and CK ($p > 0.05$). At 10–20 cm, 20–30 cm, and 30–40 cm, BD in GE was significantly lower than in CK, with an average of 11.92%, while TP in GE was significantly higher than in

TABLE 1 Characteristics of the soil mechanical composition under different grazing regimes.

Soil depth cm	Grazing practices	Sand (0.02–2 mm) %	Silt (0.002–0.02 mm) %	Clay (<0.002 mm) %
0–10	GE	75.66 ± 4.54B	18.92 ± 3.64A	5.39 ± 0.91A
	SG	72.85 ± 2.36B	21.42 ± 1.82A	5.71 ± 0.55A
	CK	84.65 ± 1.40A	11.84 ± 1.14B	3.49 ± 0.30B
10–20	GE	70.45 ± 6.42B	23.21 ± 5.04A	6.32 ± 1.38A
	SG	83.34 ± 2.22A	13.13 ± 1.91B	3.49 ± 0.31B
	CK	83.82 ± 1.85A	12.79 ± 1.27B	3.36 ± 0.59B
20–30	GE	78.17 ± 1.79A	17.42 ± 1.48A	4.37 ± 0.30A
	SG	77.33 ± 7.22A	18.14 ± 6.13A	4.49 ± 1.08A
	CK	81.56 ± 4.55A	14.22 ± 3.33A	4.18 ± 1.25A
30–40	GE	73.86 ± 2.65B	20.94 ± 1.94A	5.17 ± 0.82A
	SG	76.9 ± 4.31B	18.48 ± 3.37A	4.58 ± 0.93A
	CK	85.58 ± 1.40A	11.18 ± 1.48B	3.22 ± 0.13B

Note: Different letters represent significant differences at $p < 0.05$. GE, grazing exclusion; SG, seasonal grazing; CK, free grazing.

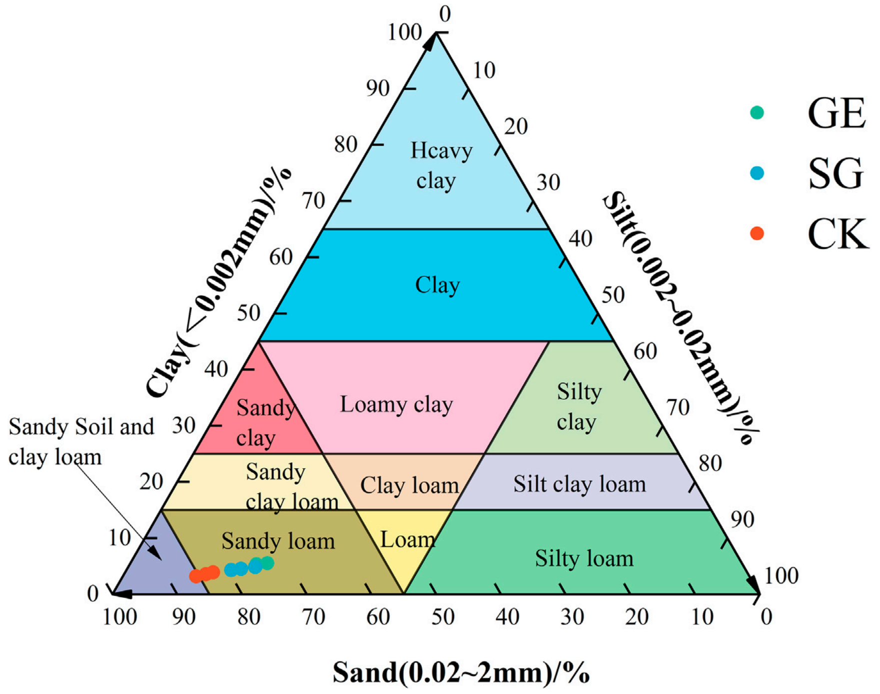


FIGURE 2
Triangular map of soil texture classification. NOTE: SG: seasonal grazing; CK: free grazing.

CK, with an average of 16.09% ($p < 0.05$). In all four soil horizons, CP in GE was significantly higher than in CK, with an average of 27.42% ($p < 0.05$), and SG and CK had no statistically significant difference ($p > 0.05$). A significant difference in NCP at 0–10 cm was only found between GE and CK($p < 0.05$). NCP showed no statistically significant differences among GE, SG, and CK in the remaining three soil horizons ($p > 0.05$).

3.3 Soil aggregate composition distribution and stability characteristics

As shown in Figure 3, grazing practices significantly influenced soil aggregate composition. In the GE and SG, the >2 mm fraction was predominant (accounting for 43.36% and 36.57%, respectively), while in the CK, the <0.25 mm fraction was predominant (35.59%). The >2 mm

TABLE 2 Characteristics of soil bulk density and porosity under different grazing practices.

Soil depth cm	Grazing practices	BD g/cm^3	TP %	CP %	NCP %
0–10	GE	1.46 ± 0.05A	45.69 ± 1.57A	29.75 ± 2.20A	15.94 ± 0.73B
	SG	1.51 ± 0.05A	44.06 ± 1.67A	27.42 ± 1.57AB	16.64 ± 0.37AB
	CK	1.55 ± 0.04A	42.67 ± 1.46A	25.14 ± 2.19B	17.53 ± 0.56A
10–20	GE	1.44 ± 0.08B	46.42 ± 2.53A	31.18 ± 4.12A	15.24 ± 1.62A
	SG	1.54 ± 0.02AB	42.89 ± 0.68AB	26.35 ± 0.65AB	16.55 ± 0.52A
	CK	1.67 ± 0.09A	38.71 ± 2.94B	22.20 ± 3.18B	16.51 ± 0.29A
20–30	GE	1.40 ± 0.08B	47.86 ± 2.71A	32.29 ± 4.21A	15.57 ± 1.54A
	SG	1.48 ± 0.04AB	45.01 ± 1.27AB	29.29 ± 1.65AB	15.72 ± 0.50A
	CK	1.60 ± 0.08A	41.10 ± 2.85B	24.69 ± 2.53B	16.41 ± 0.21A
30–40	GE	1.43 ± 0.09B	46.79 ± 2.83A	30.35 ± 4.16A	16.44 ± 1.39A
	SG	1.45 ± 0.06B	45.12 ± 2.66AB	29.13 ± 3.08A	15.82 ± 0.72A
	CK	1.58 ± 0.02A	41.81 ± 0.78B	25.27 ± 0.83A	16.54 ± 1.33A

Note: Different letters represent significant differences at $p < 0.05$. BD, soil bulk density; TP, soil total porosity; CP, soil capillary porosity; NCP, soil non-capillary porosity; GE, grazing exclusion; SG, seasonal grazing; CK, free grazing.

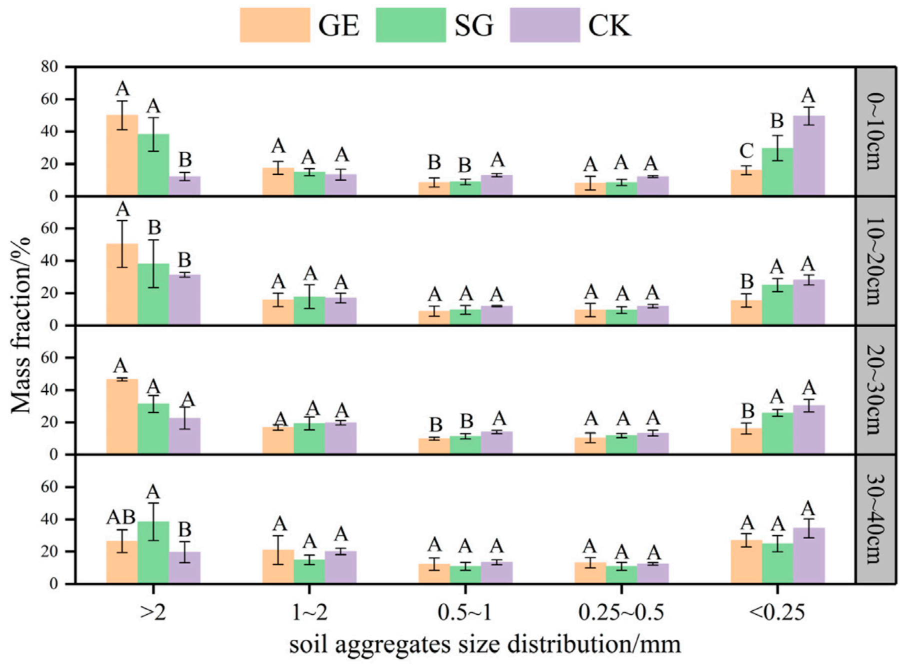


FIGURE 3
Distribution of soil aggregate size under different grazing practices. NOTE: Different letters represent significant differences at $p < 0.05$. GE: grazing exclusion; SG: seasonal grazing; CK: free grazing.

fraction content at 0–10 cm in the GE showed a statistically significant increase of 62.77% compared to the CK ($p < 0.05$). For GE, the content of the >2 mm fraction at a depth of 10–20 cm was significantly higher than that in SG and CK ($p < 0.05$), with the increases being by a factor of 1.32 and 1.61, respectively. Regarding the <0.25 mm fraction at 0–10 cm, 10–20 cm, and 20–30 cm, the values in GE were significantly lower than those in SG and CK ($p < 0.05$), while no statistical difference was detected at 30–40 cm ($p > 0.05$). In particular, for the >2 mm fraction of GE, SG, and CK, there was no statistical difference at 20–30 cm ($p > 0.05$). However, at 30–40 cm, the value for SG was significantly higher than that for CK($p < 0.05$), reaching 1.96 times that of CK.

ANOVA of the water stability of soil aggregates in Figure 4 indicated that soil aggregate stability indicators varied significantly among different grazing methods, yet the stability indicators

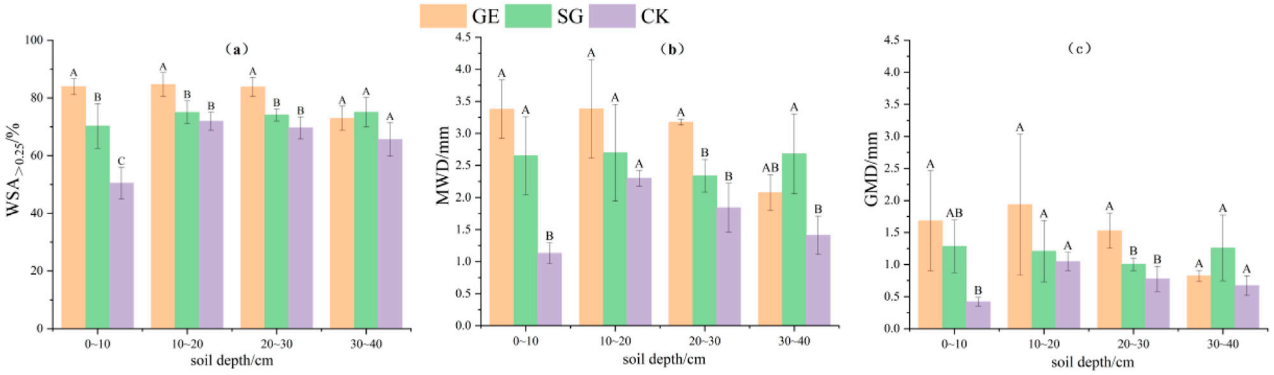


FIGURE 4
Effects of different grazing practices on WSA$_{>0.25}$ **(A)**, MWD **(B)**, GMD **(C)**, water-stability. NOTE: Different letters represent significant differences at $P < 0.05$. WSA$_{>0.25}$: content of soil aggregate >0.25 mm particle size; MWD: mean weight diameter; GMD: geometric mean diameter; GE: grazing exclusion; SG: seasonal grazing; CK: free grazing.

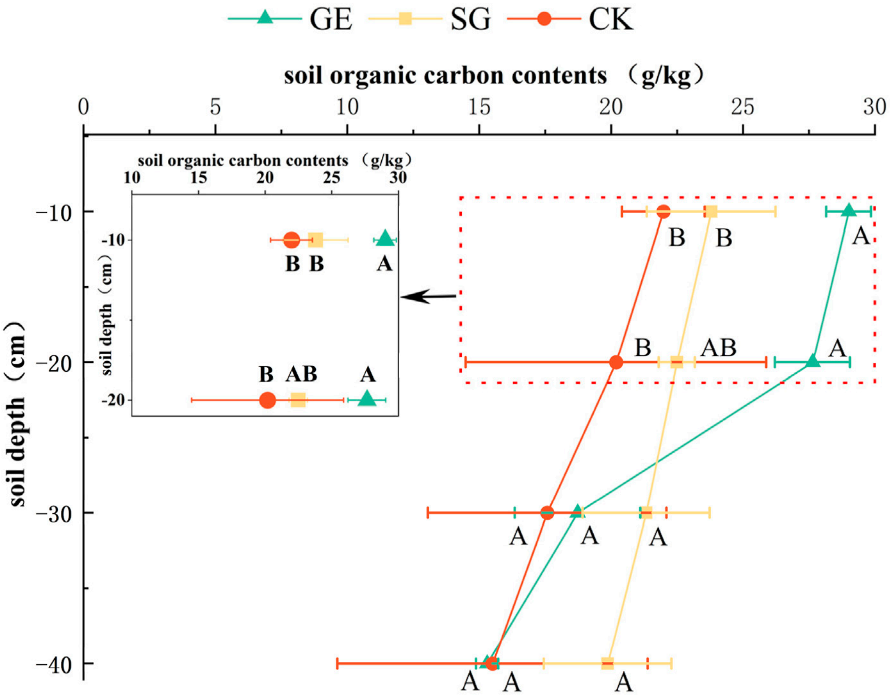
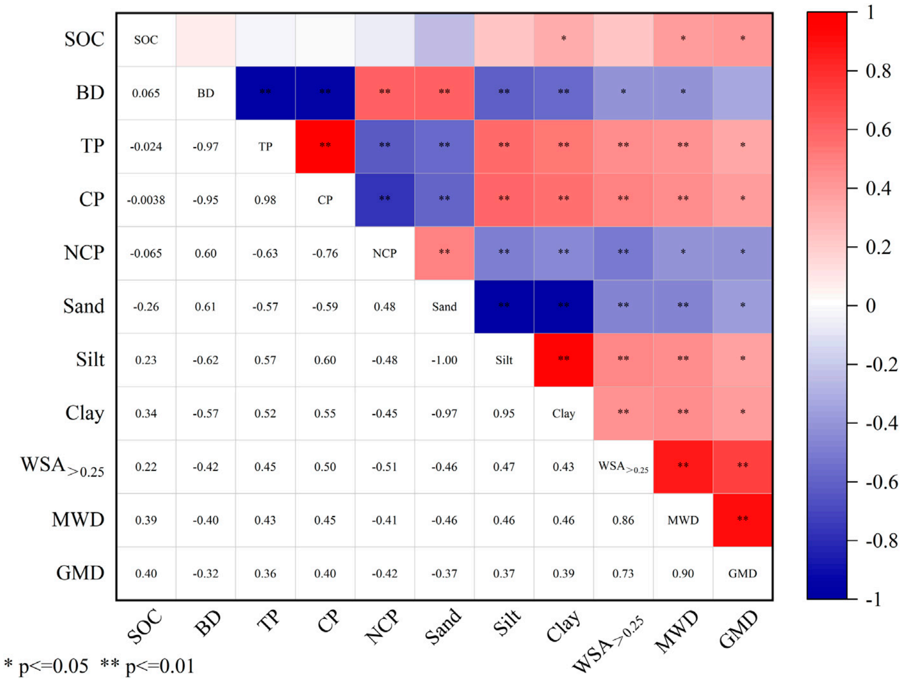


FIGURE 5
Effects of different grazing practices on SOC. NOTE: Different letters represent significant differences at $p < 0.05$. GE: grazing exclusion; SG: seasonal grazing; CK: free grazing; SOC: soil organic carbon.

exhibited a consistent trend. For the 0–30 cm layer, the following results were obtained for WSA$_{>0.25}$, MWD, and GMD: GE > SG > CK. However, at a soil depth of 30–40 cm, the results changed to SG > GE > CK. For GE, the values of WSA$>_{0.25}$, MWD, and GMD were significantly higher than those of CK at soil depths of 0–10 cm and 20–30 cm ($p < 0.05$). For SG, WSA$>_{0.25}$ and MWD values were significantly higher in 0–10 cm than in CK ($p < 0.05$). At a 0–30 cm depth, the WSA$_{>0.25}$ of GE was significantly higher than that of CK ($p < 0.05$). The highest MWD values of GE, SG, and CK were 3.38 mm, 2.70 mm, and 2.30 mm, respectively, and occurred at 10–20 cm. However, they did not reach the significance level between them ($p > 0.05$). At a depth of 30–40 cm, only the MWD of SG was significantly higher than that of CK ($p < 0.05$).

3.4 Characteristics of soil organic carbon changes

The study demonstrated that SOC decreased as soil depth increased (Figure 5). The maximum SOC in the 0–20 cm layer



	SOC	BD	TP	CP	NCP	Sand	Silt	Clay	$WSA_{>0.25}$	MWD	GMD
SOC	SOC							*		*	*
BD	0.065	BD	**	**	**	**	**	**	*	*	
TP	-0.024	-0.97	TP	**	**	**	**	**	**	**	*
CP	-0.0038	-0.95	0.98	CP	**	**	**	**	**	**	*
NCP	-0.065	0.60	-0.63	-0.76	NCP	**	**	**	**	*	*
Sand	-0.26	0.61	-0.57	-0.59	0.48	Sand	**	**	**	**	*
Silt	0.23	-0.62	0.57	0.60	-0.48	-1.00	Silt	**	**	**	*
Clay	0.34	-0.57	0.52	0.55	-0.45	-0.97	0.95	Clay	**	**	*
$WSA_{>0.25}$	0.22	-0.42	0.45	0.50	-0.51	-0.46	0.47	0.43	$WSA_{>0.25}$	**	**
MWD	0.39	-0.40	0.43	0.45	-0.41	-0.46	0.46	0.46	0.86	MWD	**
GMD	0.40	-0.32	0.36	0.40	-0.42	-0.37	0.37	0.39	0.73	0.90	GMD

FIGURE 6
Correlation analysis.NOTE:SOC: soil organic carbon; BD: soil bulk density; TP: soil total porosity; CP: soil capillary porosity; NCP: soil non-capillary porosity; $WSA_{>0.25}$: content of soil aggregate >0.25 mm particle size; MWD: mean weight diameter; GMD: geometric mean diameter.

was observed in GE, and the maximum SOC in the 20–40 cm layer was observed in SG. SOC for each grazing method decreased with soil depth. In the GE, the SOC in the 0–10 cm was found to be 1.55 times and 1.81 times that of the 20–30 cm and 30–40 cm. In the SG, the increases in SOC for the 0–10 cm and 10–20 cm in comparison to the 30–40 cm were 19.76% and 13.20%. The mean increase in the 0–10 cm under the CK compared with the 10–20 cm, 20–30 cm, and 30–40 cm was 4.22 g/kg.

At the 0–10 cm and 10–20 cm depths, GE significantly increased SOC by 7.02 mg/kg and 7.45 mg/kg, respectively, compared to the CK ($p < 0.05$). However, there was no statistically significant difference between SG and CK ($p > 0.05$). At the 20–30 cm and 30–40 cm depths, there was no statistical difference among GE, SG, and CK ($p > 0.05$).

3.5 Relationship factors influencing soil aggregate stability

Correlation analyses were performed on eleven factors, including BD, soil porosity (TP, CP and NCP), soil particle size composition (Clay, Silt, and Sand), soil aggregate stability ($WSA_{>0.25}$, MWD and GMD), and SOC (Figure 6). The results showed that most of the selected vital factors significantly impacted soil aggregate stability ($p < 0.05$). Soil porosity and particle size composition showed a significant and positive correlation with all three indicators of soil aggregates ($P < 0.05$). BD exhibited a significant negative correlation with $WSA_{>0.25}$ and MWD ($P < 0.05$). A significant positive correlation was also detected between Clay and SOC.

We used BRT modeling to quantitatively assess other indicators' effects on soil aggregate stability (Figure 7). In the process, we categorized all the relevant indicators into distinct groups. The first group is BD. The second group pertains to soil porosity and is divided into TP, CP, and NCP. The third group involves soil particle size composition consisting of clay, silt, and sand. Then, there is the SOC group. Finally, the soil aggregate stability group is characterized by $WSA_{>0.25}$, MWD, and GMD. The results indicated that porosity was the primary factor affecting soil aggregate stability, with effects of 60.05%, 40.86%, and 38.05% on $WSA_{>0.25}$, MWD, and GMD, respectively. Subsequently, SOC exerted an influence exceeding 20% on MWD and GMD, while its impact on $WSA_{>0.25}$ was limited to 13.87%. Individually, SOC had the most significant impact on MWD and GMD.

4 Discussion

4.1 Effects of grazing practices on soil structure indicators

In studies of the effects of grazing on soil structure, the time span resolves the central variable in the response mechanisms of soil ecosystems. For example, short-term (<5 years) grazing samples showed only minor variations in properties such as soil porosity (Batista et al., 2019), whereas studies of 10-year grazing samples found significant decreases in BD and clay particle fraction, but such changes are still at a more surface stage (Liu J. et al., 2017). In contrast, our observations from sample plots grazed for up to

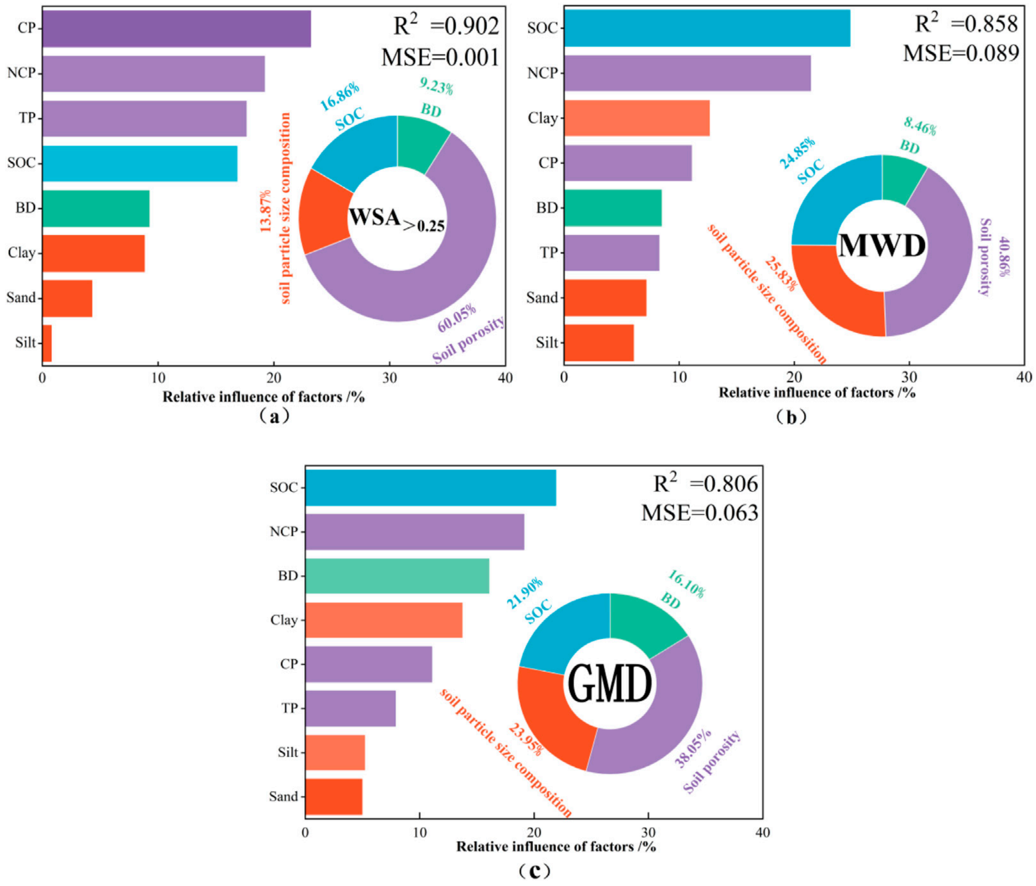


FIGURE 7
Independent effects of factors on $WSA_{>0.25}$ **(A)**, MWD **(B)**, GMD **(C)**. NOTE: BD: soil bulk density; TP: soil total porosity; CP: soil capillary porosity; NCP: soil non-capillary porosity; SOC: soil organic carbon; $WSA_{>0.25}$: content of soil aggregate >0.25 mm particle size; MWD: mean weight diameter; GMD: geometric mean diameter.

20 years are more representative of the evolution of soil structure under long-term grazing. The effects of animal trampling on rangelands are complex and intertwined with other factors that need to be analyzed independently for changes in soil parameters (Bayat et al., 2022).

The influence of grazing on soil structure is mainly due to livestock trampling, which can be divided into three main damage mechanisms: foraging, trampling, and excretion (Mayel et al., 2021). Our study indicated that following 20 years of restricted grazing, the clay of GE and SG increased (mainly from 0 to 10 cm), leading to favorable changes in soil texture (Zhang H. et al., 2019). For BD and soil porosity, we indicated that the average BD from 0 to 40 cm increased from 1.43 g/cm^3 (GE) and 1.50 g/cm^3 (SG) to 1.60 g/cm^3 (CK), while soil porosity decreased from 46.69% to 44.27%–41.07%. The compaction of soil pore space due to trampling is a remarkable phenomenon, leading to CK pastures having the lowest soil porosity (Carrero-González et al., 2012). As hypothesized by Zhang et al., the reduction in porosity resulting from grazing may be mainly due to the disappearance of macropores and larger pores (Zhang B. et al., 2019). Since pores and soil particles are mutually exclusive, the decrease in porosity and the notably corresponding increase in particle volume consequently decrease BD (Mayel et al., 2021). We inferred that this may be due to the cumulative effect of livestock trampling on BD in desert steppe (Negrón et al., 2019). In the 20-year grazing sample plots, each trampling by livestock caused a small compression of the pore space between soil particles. Over time, this compression accumulated, resulting in a significant reduction in soil pore space and a consequent increase in BD.

Additionally, livestock trampling also influences alterations in soil aggregate composition distribution. The level of pressure that livestock apply to soil particles varies depending on the particular grazing practices used. Soil structural function will inevitably deteriorate when the pressure exerted surpasses the soil's pre-compressive stress (Pc) (Dec et al., 2012; Negrón et al., 2019). The main component is large aggregates (>0.25 mm), which suggests that soil aggregation is effective and enhances resistance to livestock trampling pressure (Wang et al., 2020a).

Soil aggregate stability is an essential indicator of soil degradation and soil quality. It is mainly characterized by the following parameters: $WSA_{>0.25}$, MWD, and GMD (Boix-Fayos et al., 2001; Obalum et al., 2019). $WSA_{>0.25}$ reflects soil structure, with higher values indicating better structure; MWD and GMD indicate the proportion and size of soil aggregates, with higher values indicating better stability. The data showed a significant increase in the density of macroaggregates (>0.25 mm) within the 0–20 cm layer following the implementation of GE. MWD and GMD increased by an average of 1.05 mm in GE and 0.69 mm in SG compared to CK. It is worth noting that SG had the highest values of aggregate stability in 30–40 cm layer, followed by GE and CK, which had the lowest stability values. The GE site has >90% vegetation cover, which reduces the impact of raindrops or livestock on the soil, which in turn contributes to the stabilization of soil aggregates. Vegetation also intercepts soil particles (mainly clay) carried by wind-sand flow, which are bound at the base of the plants by the water lost by the plants and gradually form soil aggregates (Jiang et al., 2022). This may be due to the distribution of desert steppe vegetation roots related to the entanglement of roots and secretion of material that may have facilitated the formation of macroaggregates (>0.25 mm) in the region (Six and Paustian, 2014; Baumert et al., 2018). The formation of soil aggregates is intimately associated with SOC (Xue et al., 2019). The increase in SOC enhanced the generation of macroaggregates (>0.25 mm) and improved their stability, as evidenced by the increase in SOC from the 0–20 cm layer, as demonstrated in our study (Gu et al., 2024). In CK, soil aggregates with a >0.25 mm dominated. This may be associated with increased BD and decreased SOC from livestock trampling on the pastureland (Yao et al., 2019). Disintegration of macroaggregates (>0.25 mm) may also be possible due to dry-wet cycles and freeze-thaw processes (Oztas and Fayetorbay, 2003; Jesús Melej et al., 2024).

This study showed that grazing practices significantly affected surface soil organic carbon, especially at depths of 0–10 cm and 10–20 cm. The GE method significantly enhanced SOC, consistent with the observations reported by Shen (Shen et al., 2023). Macroaggregates (>2 mm) have a strong influence on SOC fixation and are the primary site of SOC storage (Wang et al., 2020b; Xi et al., 2022). Macroaggregates (>2 mm) dominated, effectively storing large amounts of SOC. Grazing had a significant effect on these large aggregates (>2 mm) at depths of 0–10 cm and 10–20 cm, with the SOC gradually dissipating as the macroaggregates (>2 mm) decomposed. The primary reason was that the soil in the desert steppe of this study was more influenced by vegetation. During the grazing period, livestock consumed mainly rhizomatous grasses, resulting in a reduction in above-ground biomass and an increase in the density and complexity of the surface root system (Li et al., 2014; Wang et al., 2014). The growth of roots enhances the conservation of carbon (Yang et al., 2023). However, the effects of grazing on SOC remain controversial, with studies indicating that grazing can increase (Hewins et al., 2018; Shen et al., 2023), decrease (Zhao et al., 2009; Dlamini et al., 2016; Ren et al., 2024) or leave SOC unchanged (Derner et al., 2019). This controversy may arise from differences in the climatic zones studied and the negative impact of climate change on livestock production (Ghahramani et al., 2019; Li et al., 2022). The study area is in an arid and semi-arid zone and is severely constrained by water resources. Grazing increases greenhouse gas emissions and turns grasslands into carbon sources, and prolonged drought alters biogeochemical cycles and organic carbon storage (Pinay et al., 2007). Under warm and humid climatic conditions, grazing favors SOC production due to the accelerated decomposition of plant residues and elevated soil microbial carbon (Abdalla et al., 2018). Another possibility is the effect of the stocking rate, where low stocking rate grazing promotes vegetation diversity and increases SOC due to increased above-ground biomass of communities (Gebregergs et al., 2019). Conversely, large aggregations of livestock foraging cause significant vegetation reductions, leading to a reduction in readily decomposable herb litter mediates, ultimately reducing SOC (Liu S. et al., 2017).

4.2 Relationship factors influencing the soil aggregate stability

The correlation analysis and the results of the BRT analysis indicate that soil aggregate stability is mainly dependent on soil porosity (Rabot et al., 2018; Menon et al., 2020; Ajayi et al., 2021). The data indicated that soil porosity contributed 60.05%, 40.86%, and 38.05% to the $WSA_{>0.25}$, MWD, and GMD changes. Pore space accommodates air entering the soil aggregate. The increase in pore volume and connectivity reduces the expansion pressure of the pores, thus increasing the stability of the soil aggregates (Bisdom et al., 1993). Furthermore, the pore space is an active area for soil microorganisms and microfauna communities. Microorganisms metabolize, reproduce, and secrete organic substances in the pore space. Exopolysaccharides secreted by soil microorganisms gel with clay particles to form soil aggregates (Pokharel et al., 2013; Walshire et al., 2024). In addition, the microorganisms carry an electrical charge that promotes soil particle adhesion and facilitates soil aggregates' formation through electrostatic attraction (Coban et al., 2022). Pores are conduits for physicochemical and biological processes ultimately work together to form soil aggregate stability (Yudina and Kuzyakov, 2023).

SOC plays an essential and irreplaceable role in the formation mechanism of soil aggregates and in maintaining soil aggregate stability (Dong et al., 2020; Fei et al., 2021). The outcomes of our research substantiated this claim, with an average impact of SOC on the soil aggregate stability amounting to 21.17%. This result is consistent with the findings in subtropical China that SOC is the driver factor of soil aggregate stability and plays the role of a cementing agent during soil aggregate formation (Xue et al., 2019). A higher content of SOC can increase the negative charge density on the surface of soil particles and promote the repulsive force and attractive force between soil particles to reach a more stable equilibrium state (Yu et al., 2017). This is conducive to maintaining the structural integrity of soil aggregates in the face of disturbances caused by external environmental factors and reduces the risk of disintegration and dispersion (Kan et al., 2022).

5 Conclusion

Following 2 decades of management, Both grazing practices enhanced soil structure, which exhibited variations at different soil depths. SG significantly improved the clay (<0.002 mm), silt (0.002–0.02 mm), macroaggregates (>0.25 mm), aggregate stability, and SOC within the 0–10 cm soil layer. However, for GE, the significant improvement of these indicators extends down to a depth of 20 cm. In particular, after 20 years of restricted grazing, BD decreased, soil porosity increased, and soil texture improved. Thus, soil structure can be enhanced by limiting grazing with optimal improvement in GE, which can be used to restore degraded desert steppe. Soil porosity exerts the most significant influence on the soil aggregate stability, with an average expanation of more than 45%, with SOC ranking second in terms of influence. Further insights into the interconnection between soil aggregate stability and soil porosity in desert steppe are offered.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YY: Data curation, Formal Analysis, Investigation, Writing–original draft. ZM: Conceptualization, Funding acquisition, Methodology, Writing–review and editing. HL: Data curation, Investigation, Visualization, Writing–original draft. YG: Data curation, Investigation, Writing–original draft. TL: Investigation, Writing–original draft. LQ: Investigation, Writing–original draft.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This research was supported by the National Key Research and Development Project of China (2024YFF1306305), and the Basic Research Funds for Universities-Innovation Team Building-Desert Ecosystem Protection and Restoration Innovation Team (BR22-13-03).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

References

Abdalla, M., Hastings, A., Chadwick, D. R., Jones, D. L., Evans, C. D., Jones, M. B., et al. (2018). Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. *Agr. Ecosyst. Environ.* 253, 62–81. doi:10.1016/j.agee.2017.10.023

Abu-Hamdeh, N. H., Abo-Qudais, S. A., and Othman, A. M. (2006). Effect of soil aggregate size on infiltration and erosion characteristics. *Eur. J. Soil Sci.* 57, 609–616. doi:10.1111/j.1365-2389.2005.00743.x

Ajayi, A. E., Faloye, O. T., Reinsch, T., and Horn, R. (2021). Changes in soil structure and pore functions under long term/continuous grassland management. *Agr. Ecosyst. Environ.* 314, 107407. doi:10.1016/j.agee.2021.107407

Bardgett, R. D., Bullock, J. M., Lavorel, S., Manning, P., Schaffner, U., Ostle, N., et al. (2021). Combatting global grassland degradation. *Nat. Rev. Earth Environ.* 2, 720–735. doi:10.1038/s43017-021-00207-2

Batista, P. H. D., De Almeida, G. L. P., De Lima, R. P., Pandorfi, H., Da Silva, M. V., and Rolim, M. M. (2019). Impact of short-term grazing on physical properties of planosols in northeastern Brazil. *Geoderma Reg.* 19, e00234. doi:10.1016/j.geodrs.2019.e00234

Baumert, V. L., Vasilyeva, N. A., Vladimirov, A. A., Meier, I. C., Kögel-Knabner, I., and Mueller, C. W. (2018). Root exudates induce soil macroaggregation facilitated by fungi in subsoil. *Front. Environ. Sci.* 6, 140. doi:10.3389/fenvs.2018.00140

Bayat, H., Sheklabadi, M., Moradhaseli, M., Rastgou, M., and Gregory, A. S. (2022). Grazing management, slope aspect and canopy effects on the compression characteristic of soils of the Gonbad experimental watershed in Hamedan, Iran. *Geoderma* 409, 115641. doi:10.1016/j.geoderma.2021.115641

Bisdom, E. B. A., Dekker, L. W., and Schoute, J. F.Th. (1993). Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure. *Geoderma* 56, 105–118. doi:10.1016/0016-7061(93)90103-R

Blanco, H., and Lal, R. (2023). "Management of grazing lands," in *Soil conservation and management* (Cham: Springer Nature Switzerland), 443–469. doi:10.1007/978-3-031-30341-8_18

Blanco-Sepúlveda, R., Gómez-Moreno, M. L., and Lima, F. (2024). An approach to the key soil physical properties for assessing soil compaction due to livestock grazing in mediterranean mountain areas. *Sustainability* 16, 4279. doi:10.3390/su16104279

Boix-Fayos, C., Calvo-Cases, A., Imeson, A. C., and Soriano-Soto, M. D. (2001). Influence of soil properties on the aggregation of some Mediterranean soils and the use of aggregate size and stability as land degradation indicators. *Catena* 44, 47–67. doi:10.1016/S0341-8162(00)00176-4

Carrero-González, B., De La Cruz, M. T., and Casermeiro, M. A. (2012). Application of Magnetic Resonance Techniques to evaluate soil compaction after grazing. *J. Soil Sci. Plant Nutr.* 12, 165–182. doi:10.4067/S0718-95162012000100014

Chen, L., and Baoyin, T. (2024). Effects of plant productivity and species on soil carbon and nitrogen sequestration under seasonal grazing in a semi-arid grassland of north China. *Land Degrad. Dev.* 35, 1960–1970. doi:10.1002/ldr.5035

Coban, O., De Deyn, G. B., and Van Der Ploeg, M. (2022). Soil microbiota as game-changers in restoration of degraded lands. *Science* 375, abe0725. doi:10.1126/science.abe0725

Conte, T. J., and Tilt, B. (2014). The effects of China's grassland contract policy on pastoralists' attitudes towards cooperation in an inner Mongolian banner. *Hum. Ecol.* 42, 837–846. doi:10.1007/s10745-014-9690-4

De Boer, H. C., Deru, J. G. C., and Van Eekeren, N. (2018). Sward lifting in compacted grassland: effects on soil structure, grass rooting and productivity. *Soil Tillage. Res.* 184, 317–325. doi:10.1016/j.still.2018.07.013

Dec, D., Dörner, J., Balocchi, O., and López, I. (2012). Temporal dynamics of hydraulic and mechanical properties of an Andosol under grazing. *Soil Tillage. Res.* 125, 44–51. doi:10.1016/j.still.2012.05.018

Deng, L., Kim, D., Peng, C., and Shangguan, Z. (2018). Controls of soil and aggregate-associated organic carbon variations following natural vegetation restoration on the L oess P lateau in C hina. *Land Degrad. Dev.* 29, 3974–3984. doi:10.1002/ldr.3142

Derner, J. D., Augustine, D. J., and Frank, D. A. (2019). Does grazing matter for soil organic carbon sequestration in the western north American great plains? *Ecosystems* 22, 1088–1094. doi:10.1007/s10021-018-0324-3

Dlamini, P., Chivenge, P., and Chaplot, V. (2016). Overgrazing decreases soil organic carbon stocks the most under dry climates and low soil pH: a meta-analysis shows. *Agr. Ecosyst. Environ.* 221, 258–269. doi:10.1016/j.agee.2016.01.026

Dong, L., Zheng, Y., Martinsen, V., Liang, C., and Mulder, J. (2022). Effect of grazing exclusion and rotational grazing on soil aggregate stability in typical grasslands in inner Mongolia, China. *Front. Environ. Sci.* 10, 844151. doi:10.3389/fenvs.2022.844151

Dong, S., Zhang, J., Li, Y., Liu, S., Dong, Q., Zhou, H., et al. (2020). Effect of grassland degradation on aggregate-associated soil organic carbon of alpine grassland ecosystems in the Qinghai-Tibetan Plateau. *Eur. J. Soil Sci.* 71, 69–79. doi:10.1111/ejss.12835

Egashlra, K., Kaetsu, Y., and Takuma, K. (1983). Aggregate stability as an index of erodibility of ando soils. *Soil Sci. Plant Nutr.* 29, 473–481. doi:10.1080/00380768.1983.10434650

Enriquez, A. S., Necpalova, M., Cremona, M. V., Peri, P. L., and Six, J. (2021). Immobilization and stabilization of volcanic ash in soil aggregates in semiarid meadows of Northern Patagonia. *Geoderma* 392, 114987. doi:10.1016/j.geoderma.2021.114987

Fei, C., Zhang, S., Li, J., Liang, B., and Ding, X. (2021). Partial substitution of rice husks for manure in greenhouse vegetable fields: insight from soil carbon stock and aggregate stability. *Land Degrad. Dev.* 32, 3962–3972. doi:10.1002/ldr.4021

Ferreira, T. R., Archilha, N. L., Cássaro, F. A. M., and Pires, L. F. (2023). How can pore characteristics of soil aggregates from contrasting tillage systems affect their intrinsic permeability and hydraulic conductivity? *Soil Tillage. Res.* 230, 105704. doi:10.1016/j.still.2023.105704

Franzluebbers, A. J., Endale, D. M., Buyer, J. S., and Stuedemann, J. A. (2012). Tall fescue management in the piedmont: sequestration of soil organic carbon and total nitrogen. *Soil Sci. Soc. Am. J.* 76, 1016–1026. doi:10.2136/sssaj2011.0347

Gao, H., Song, X., Wu, X., Zhang, N., Liang, T., Wang, Z., et al. (2024). Interactive effects of soil erosion and mechanical compaction on soil DOC dynamics and CO2 emissions in sloping arable land. *Catena* 238, 107906. doi:10.1016/j.catena.2024.107906

Gebregergs, T., Tessema, Z. K., Solomon, N., and Birhane, E. (2019). Carbon sequestration and soil restoration potential of grazing lands under exclosure management in a semi-arid environment of northern Ethiopia. *Ecol. Evol.* 9, 6468–6479. doi:10.1002/ece3.5223

Ghahramani, A., Howden, S. M., Del Prado, A., Thomas, D. T., Moore, A. D., Ji, B., et al. (2019). Climate change impact, adaptation, and mitigation in temperate grazing systems: a review. *Sustainability* 11, 7224. doi:10.3390/su11247224

Gu, W., Wang, Y., Sun, Y., Liu, Z., Wang, W., Wu, D., et al. (2024). Assessing the formation and stability of paddy soil aggregate driven by organic carbon and Fe/Al oxides in rice straw cyclic utilization strategies: insight from a six-year field trial. *Sci. Total Environ.* 951, 175607. doi:10.1016/j.scitotenv.2024.175607

Hewins, D. B., Lyseng, M. P., Schoderbek, D. F., Alexander, M., Willms, W. D., Carlyle, C. N., et al. (2018). Grazing and climate effects on soil organic carbon concentration and particle-size association in northern grasslands. *Sci. Rep.* 8, 1336. doi:10.1038/s41598-018-19785-1

Jesús Melej, M., Acevedo, S. E., Contreras, C. P., Giraldo, C. V., Maurer, T., Calderón, F. J., et al. (2024). Changes in macroaggregate stability as a result of wetting/drying cycles of soils with different organic matter and clay contents. *Geoderma* 448, 116965. doi:10.1016/j.geoderma.2024.116965

Jiang, L., Hu, D., and Lv, G. (2022). The edaphic and vegetational properties controlling soil aggregate stability vary with plant communities in an arid desert region of northwest China. *Forests* 13, 368. doi:10.3390/f13030368

Kan, Z., Liu, W., Liu, W., Lal, R., Dang, Y. P., Zhao, X., et al. (2022). Mechanisms of soil organic carbon stability and its response to no-till: a global synthesis and perspective. *Glob. Change Biol.* 28, 693–710. doi:10.1111/gcb.15968

Karlen, D. L., and Stott, D. E. (2015). "A framework for evaluating physical and chemical indicators of soil quality," in *SSSA special publications*. Editors J. W. Doran, D. C. Coleman, D. F. Bezdicek, and B. A. Stewart (Madison, WI, USA: Soil Science Society of America and American Society of Agronomy), 53–72. doi:10.2136/sssaspecpub35.c4

Kinnell, P. I. A. (2018). Determining soil erodibilities for the USLE-MM rainfall erosion model. *Catena* 163, 424–426. doi:10.1016/j.catena.2018.01.008

Lai, L., and Kumar, S. (2020). A global meta-analysis of livestock grazing impacts on soil properties. *PLOS One* 15, e0236638. doi:10.1371/journal.pone.0236638

Li, C., Han, Q., and Xu, W. (2022). Contribution of climate change and grazing on carbon dynamics in central asian pasturelands. *Remote Sens-Basel* 14, 1210. doi:10.3390/rs14051210

Li, S., Yu, F., Werger, M. J. A., Dong, M., Ramula, S., and Zuidema, P. A. (2013). Understanding the effects of a new grazing policy: the impact of seasonal grazing on shrub demography in the Inner Mongolian steppe. *J. Appl. Ecol.* 50, 1377–1386. doi:10.1111/1365-2664.12159

Li, Y., Zhu, Y., Zhao, J., Li, G., Wang, H., Lai, X., et al. (2014). Effects of rest grazing on organic carbon storage in Stipa grandis steppe in inner Mongolia, China. *J. Integr. Agr.* 13, 624–634. doi:10.1016/S2095-3119(13)60720-0

Liu, J., Wu, J., Su, H., Gao, Z., and Wu, Z. (2017a). Effects of grazing exclusion in xilin gol grassland differ between regions. *Ecol. Eng.* 99, 271–281. doi:10.1016/j.ecoleng.2016.11.041

Liu, S., Yang, X., Ives, A. R., Feng, Z., and Sha, L. (2017b). Effects of seasonal and perennial grazing on soil fauna community and microbial biomass carbon in the subalpine meadows of yunnan, southwest China. *Pedosphere* 27, 371–379. doi:10.1016/S1002-0160(17)60325-4

Liu, Y., Liu, X., Zhao, C., Wang, H., and Zang, F. (2023). The trade-offs and synergies of the ecological-production-living functions of grassland in the qilian mountains by ecological priority. *J. Environ. Manage.* 327, 116883. doi:10.1016/j.jenvman.2022.116883

Martens, D. (2000). Plant residue biochemistry regulates soil carbon cycling and carbon sequestration. *Soil Biol. biochem.* 32, 361–369. doi:10.1016/S0038-0717(99)00162-5

Mayel, S., Jarrah, M., and Kuka, K. (2021). How does grassland management affect physical and biochemical properties of temperate grassland soils? A review study. *Grass Forage Sci.* 76, 215–244. doi:10.1111/gfs.12512

Menon, M., Mawodza, T., Rabbani, A., Blaud, A., Lair, G. J., Babaei, M., et al. (2020). Pore system characteristics of soil aggregates and their relevance to aggregate stability. *Geoderma* 366, 114259. doi:10.1016/j.geoderma.2020.114259

Nael, M., Salarinik, K., and Assadian, G. (2024). Soil quality and vegetation cover characteristics as influenced by diverse grazing regimes and soil disturbance histories in a semi-arid rangeland (Iran). *Arid. Land Res. Manag.* 38, 318–342. doi:10.1080/15324982.2024.2309495

Negrón, M., López, I., and Dörner, J. (2019). Consequences of intensive grazing by dairy cows of contrasting live weights on volcanic ash topsoil structure and pasture dynamics. *Soil Tillage. Res.* 189, 88–97. doi:10.1016/j.still.2018.12.025

Noulèkoun, F., Birhane, E., Kassa, H., Berhe, A., Gebremichael, Z. M., Adem, N. M., et al. (2021). Grazing exclosures increase soil organic carbon stock at a rate greater than "4 per 1000" per year across agricultural landscapes in Northern Ethiopia. *Sci. Total Environ.* 782, 146821. doi:10.1016/j.scitotenv.2021.146821

Obalum, S. E., Uteau-Puschmann, D., and Peth, S. (2019). Reduced tillage and compost effects on soil aggregate stability of a silt-loam Luvisol using different aggregate stability tests. *Soil Tillage. Res.* 189, 217–228. doi:10.1016/j.still.2019.02.002

Oztas, T., and Fayetorbay, F. (2003). Effect of freezing and thawing processes on soil aggregate stability. *Catena* 52, 1–8. doi:10.1016/S0341-8162(02)00177-7

Phefadu, K. C., and Munjonji, L. (2024). Assessing the impact of no-tillage duration on soil aggregate size distribution, stability and aggregate associated organic carbon. *Agronomy* 14, 2482. doi:10.3390/agronomy14112482

Pinay, G., Barbera, P., Carreras-Palou, A., Fromin, N., Sonié, L., Madeleine Couteaux, M., et al. (2007). Impact of atmospheric CO2 and plant life forms on soil microbial activities. *Soil Biol. biochem.* 39, 33–42. doi:10.1016/j.soilbio.2006.05.018

Pokharel, A. K., Jannoura, R., Heitkamp, F., Kleikamp, B., Wachendorf, C., Dyckmans, J., et al. (2013). Development of aggregates after application of maize residues in the presence of mycorrhizal and non-mycorrhizal pea plants. *Geoderma* 202–203, 38–44. doi:10.1016/j.geoderma.2013.03.005

Rabot, E., Wiesmeier, M., Schlüter, S., and Vogel, H.-J. (2018). Soil structure as an indicator of soil functions: a review. *Geoderma* 314, 122–137. doi:10.1016/j.geoderma.2017.11.009

Reinhart, K. O., Sanni Worogo, H. S., Rinella, M. J., and Vermeire, L. T. (2021). Livestock increase soil organic carbon in the northern great plains. *Rangel. Ecol. Manag.* 79, 22–27. doi:10.1016/j.rama.2021.07.006

Ren, S., Terrer, C., Li, J., Cao, Y., Yang, S., and Liu, D. (2024). Historical impacts of grazing on carbon stocks and climate mitigation opportunities. *Nat. Clim. Chang.* 14, 380–386. doi:10.1038/s41558-024-01957-9

Rojas-Briales, E. (2015). Sparing grasslands: FAO's active role. *Science* 347, 1211. doi:10.1126/science.347.6227.1211

Romero-Ruiz, A., Monaghan, R., Milne, A., Coleman, K., Cardenas, L., Segura, C., et al. (2023). Modelling changes in soil structure caused by livestock treading. *Geoderma* 431, 116331. doi:10.1016/j.geoderma.2023.116331

Schweizer, S. A., Bucka, F. B., Graf-Rosenfellner, M., and Kögel-Knabner, I. (2019). Soil microaggregate size composition and organic matter distribution as affected by clay content. *Geoderma* 355, 113901. doi:10.1016/j.geoderma.2019.113901

Shen, Y., Fang, Y., Chen, H., Ma, Z., Huang, C., Wu, X., et al. (2023). New insights into the relationships between livestock grazing behaviors and soil organic carbon stock in an alpine grassland. *Agr. Ecosyst. Environ.* 355, 108602. doi:10.1016/j.agee.2023.108602

Sidhu, B. S., Mehrabi, Z., Ramankutty, N., and Kandlikar, M. (2023). How can machine learning help in understanding the impact of climate change on crop yields? *Environ. Res. Lett.* 18, 024008. doi:10.1088/1748-9326/acb164

Six, J., and Paustian, K. (2014). Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. *Soil Biol. biochem.* 68, A4–A9. doi:10.1016/j.soilbio.2013.06.014

Tian, L., Bai, Y., Wang, W., Qu, G., Deng, Z., Li, R., et al. (2021). Warm- and cold-season grazing affect plant diversity and soil carbon and nitrogen sequestration differently in Tibetan alpine swamp meadows. *Plant Soil* 458, 151–164. doi:10.1007/s11104-020-04573-6

Walshire, L. A., Zhang, H., Nick, Z. H., Breland, B. R., Runge, K. A., and Han, F. X. (2024). Modification of surface properties of clay minerals with exopolysaccharides from *rhizobium tropici*. *ACS Earth Space Chem.* 8, 137–147. doi:10.1021/acsearthspacechem.3c00296

Wang, J., Zhao, C., Zhao, L., Wen, J., and Li, Q. (2020a). Effects of grazing on the allocation of mass of soil aggregates and aggregate-associated organic carbon in an alpine meadow. *PLoS ONE* 15, e0234477. doi:10.1371/journal.pone.0234477

Wang, J., Zhao, C., Zhao, L., Wen, J., and Li, Q. (2020b). Effects of grazing on the allocation of mass of soil aggregates and aggregate-associated organic carbon in an alpine meadow. *PLoS ONE* 15, e0234477. doi:10.1371/journal.pone.0234477

Wang, Z., Jiao, S., Han, G., Zhao, M., Ding, H., Zhang, X., et al. (2014). Effects of stocking rate on the variability of peak standing crop in a Desert Steppe of eurasia grassland. *Environ. Manag.* 53, 266–273. doi:10.1007/s00267-013-0186-6

Xi, Y., Shao, M., Li, T., Gan, M., Chen, M., and Li, Z. (2022). Soil macroaggregates determine soil organic carbon in the natural grasslands of the loess plateau. *Catena* 218, 106533. doi:10.1016/j.catena.2022.106533

Xiao, H., Liu, G., Liu, P., Zheng, F., Zhang, J., and Hu, F. (2017). Developing equations to explore relationships between aggregate stability and erodibility in ultisols of subtropical China. *Catena* 157, 279–285. doi:10.1016/j.catena.2017.05.032

Xue, B., Huang, L., Huang, Y., Yin, Z., Li, X., and Lu, J. (2019). Effects of organic carbon and iron oxides on soil aggregate stability under different tillage systems in a rice–rape cropping system. *Catena* 177, 1–12. doi:10.1016/j.catena.2019.01.035

Yang, J., Zhang, R., Cao, R., Dong, S., Baoyin, T., and Zhao, T. (2024). Seasonal grazing does not significantly alter the particle structure and pore characteristics of grassland soil. *Land* 13, 730. doi:10.3390/land13060730

Yang, X., Wang, B., Fakher, A., An, S., and Kuzyakov, Y. (2023). Contribution of roots to soil organic carbon: from growth to decomposition experiment. *Catena* 231, 107317. doi:10.1016/j.catena.2023.107317

Yao, Y., Ge, N., Yu, S., Wei, X., Wang, X., Jin, J., et al. (2019). Response of aggregate associated organic carbon, nitrogen and phosphorous to re-vegetation in agro-pastoral ecotone of northern China. *Geoderma* 341, 172–180. doi:10.1016/j.geoderma.2019.01.036

Ye, R., Yu, W., Yang, D., Yi, F., Zhang, P., Qiu, X., et al. (2023). Effects of precipitation and grazing on the diversity and productivity of desert steppe. *Land Degrad. Dev.* 34, 2622–2635. doi:10.1002/ldr.4635

Yu, Z., Zhang, J., Zhang, C., Xin, X., and Li, H. (2017). The coupling effects of soil organic matter and particle interaction forces on soil aggregate stability. *Soil Tillage. Res.* 174, 251–260. doi:10.1016/j.still.2017.08.004

Yudina, A., and Kuzyakov, Y. (2019). Saving the face of soil aggregates. *Glob. Change Biol.* 25, 3574–3577. doi:10.1111/gcb.14779

Yudina, A., and Kuzyakov, Y. (2023). Dual nature of soil structure: the unity of aggregates and pores. *Geoderma* 434, 116478. doi:10.1016/j.geoderma.2023.116478

Zhang, B., Beck, R., Pan, Q., Zhao, M., and Hao, X. (2019a). Soil physical and chemical properties in response to long-term cattle grazing on sloped rough fescue grassland in the foothills of the Rocky Mountains, Alberta. *Geoderma* 346, 75–83. doi:10.1016/j.geoderma.2019.03.029

Zhang, H., Zhang, L., Xu, Y., Wang, Z., and Lu, Y. (2019b). Characteristics of soil texture changes of soft rock and sand compound soil with different planting years. *IOP Conf. Ser. Earth Environ. Sci.* 300, 022122. doi:10.1088/1755-1315/300/2/022122

Zhang, M., Li, X., Wang, H., and Huang, Q. (2018). Comprehensive analysis of grazing intensity impacts soil organic carbon: a case study in typical steppe of inner Mongolia, China. *Appl. Soil Ecol.* 129, 1–12. doi:10.1016/j.apsoil.2018.03.008

Zhao, H.-L., He, Y.-H., Zhou, R.-L., Su, Y.-Z., Li, Y.-Q., and Drake, S. (2009). Effects of desertification on soil organic C and N content in sandy farmland and grassland of Inner Mongolia. *Catena* 77, 187–191. doi:10.1016/j.catena.2008.12.007

Zhu, G., Deng, L., and Shangguan, Z. (2018). Effects of soil aggregate stability on soil N following land use changes under erodible environment. *Agr. Ecosyst. Environ.* 262, 18–28. doi:10.1016/j.agee.2018.04.012

Zhu, G., Yuan, C., Gong, H., Peng, Y., Huang, C., Wu, C., et al. (2021). Effects of short-term grazing prohibition on soil physical and chemical properties of meadows in Southwest China. *Peerj* 9, e11598. doi:10.7717/peerj.11598